Wide Bandwidth, Nonmagnetic Linear Optical Isolators based on Frequency Conversion

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Abstract: We propose a family of nonmagnetic optical isolators based on waveguide frequency conversion and characterized by good isolation properties, high linearity, bandwidth as high as a few THz.

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Nonreciprocal light propagation that breaks the time-reversal symmetry plays an important role in optical communication and computing. For example, optical isolators and circulator are used in laser protection, optical signal processing and instrumetation application. To break the reciprocity, optical isolation has been traditionally achieved through magneto-optical Faraday effectHowever, for the fast-developing silicon integrated photonics, the traditional optical isolators and circulators are at disadvantage as are not compatible with complementary metal-oxide-semiconductor (CMOS) processing platforms.

To avoid the integration of magneto-optical elements and achieve more compact isolation, a variety of different physical principles have been proposed. Among these new principles, one of the most attractive and studied is to bre there year based on the electro-optical effect [1,2]. In eelctro-optic modulation velocities of RF and Optical waves are matched only in one direction, and this breaks reciprocity. However, tmodulated scheems usually suffer from a number of limitations, such as incomplete isolation, nonlinearity, excessive insertion loss and narrow bandwidth, moreover, because the momentum mismatch Δk inhibiting the backward transmisison is very small, hence the achieved optical isolator is very long (~cm), which makes it harder for miniaturization. By considering the above drawbacks of electro-optical effect, we can resort to another widely used and relatively mature principle: nonlinear frequency conversion and four wave mixing (FWM) based on the second and third-order nonlinear susceptibilities $\chi^{(2)}$, $\chi^{(3)}$, which can help us obtain wide bandwidth, linear optical isolators. In this work, two ideas have been developed to achieve full isolation over wide bandwidth of a few THz in the telecom range.

First of all, we consider a nonreciprocal optical device based on the nearly degenerate parametric down frequency conversion, and up frequency conversion using second-order nonlinear ($\chi^{(2)}$) waveguides whose operational principle is shown in Figs. 5(a-d). Such waveguides have been successfully demonstrated using a number of different materials, such as lithium niobite [3]. For the down conversion which is difference frequency generation (DFG), as shown in Fig. 1(a), the forward propagating input signal wave of frequency ω_s , passes through the high pass filter (HPF) and enters the nonlinear waveguide. Also entering the waveguide is the pump wave with frequency $\omega_p < 2\omega_s$ (slightly less that twice). In the waveguide the energy of the pump is transferred to the forward propagating idler wave with the frequency $\omega_i = \omega_p - \omega_s$, slightly lower than ω_s as long as the phase matching condition $k_i + k_s = k_p$ is satisfied. At the exit, the idler wave that now carries all the information faithfully transferred from the signal passes through the low pass filter (LPF) and propagates further on. When the direction is reversed, as shown in Fig. 1(b), only the backward idler wave can pass through the LPF but when it enters the nonlinear waveguide the phase matching cannot be realized since the pump is unidirectional, therefore no signal wave is generated, and the idler wave gets absorbed by the HPF at the output. For the optical based on sum-frequency generation, as shown in Figs. 1(c-d), it follows the same story. For the material of nonlinear waveguide, we use the periodically poled Lithium Niobite (PPLN), which is a mature and wide-spread technology that had been successfully integrated with Si photonics [4]. Even though the optical isolator relies upon nonlinear effects, the input-output characteristic of the device is perfectly linear and does not depend on the input power. This is the salient distinctive feature which separates the proposed method from other nonlinear schemes.

The above proposed optical isolators require an out-of-band pump, for the telecom range isolation, the pump must operate around 780nm, which makes it difficult for integration on silicon platform. To avoid this shortcoming, we can utilize the four-wave mixing (FWM), enable by the third-order nonlinearity $\chi^{(3)}$. In the FWM process, the energy of two pump photons at frequency ω_p is transferred to the signal and idler photons with both energy $\omega_s + \omega_i = 2\omega_p$ and moment $k_s + k_i = 2k_p$ being conserved. As shown in Fig. 1(f), all three wavelengths are located in the same spectral region. To obtain strong third-order nonlinear effect, we use the active media with gain, such as semiconductor optical amplifiers (SOAs), which allows us to achieve a full frequency conversion at only a few mW of pump power. The optical isolator in Fig. 1(f) consists a SOA sandwiched between two multiplexer/de-multiplexers, which can be made from standard wavelength division multiplexing (WDM) components. The input and pump signals are combined in the input WDM and enter the SOA where the information is transferred to the idler generated by the FWM that is later separated from the spurious input and residual pump in the output WDM. When the idler is incident from the right-hand side the phase matching is no longer satisfied, and the idler wave gets blocked by the input WDM.

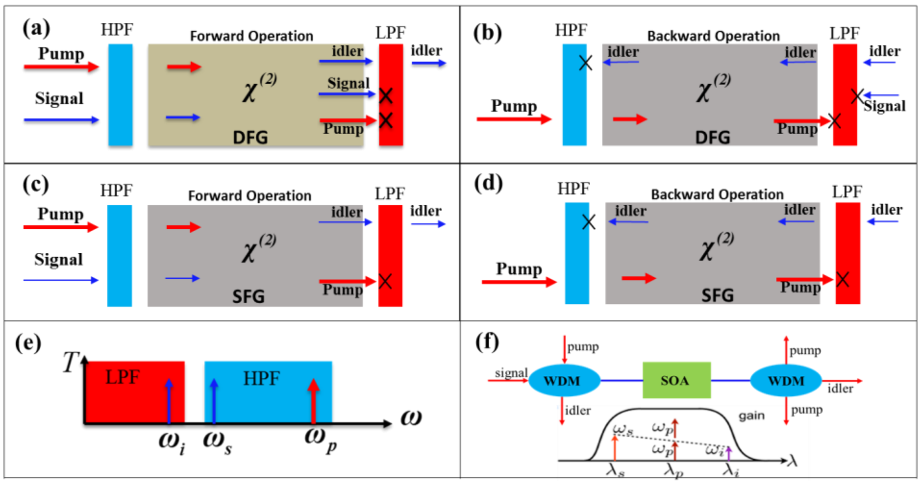

Fig. 1. Operating principle of the optical isolators. (a), (b) Optical isolator based on DFG in nonlinear waveguide for forward and backward operation; (c), (d) Optical isolator based on SFG in nonlinear waveguide for forward and backward operation. (e) Schematic of the frequency coverage of LPF and HPF; (f) Optical isolator based on Four wave mixing in SOA's.

For the implementation of the above proposed optical isolators, Fig. 2(a) shows the experimental setup for the optical isolator based on DFG, and Fig. 2(b) is the estimated performance of the optical isolator based on DFG, our preliminary calculation shows that using 100 mW pump, we can get 100% conversion for the length of 5mm.

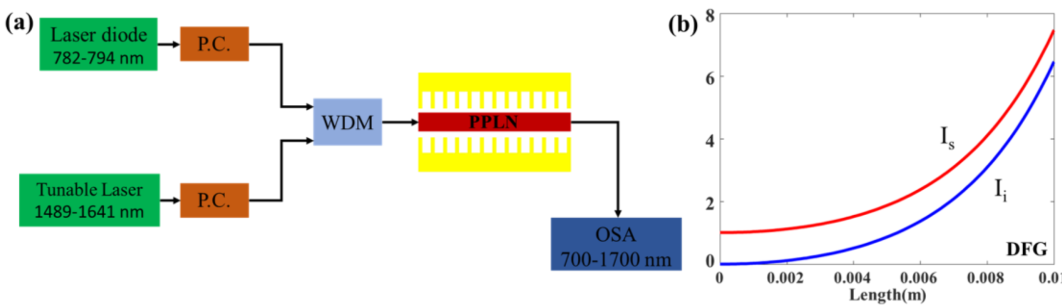

Fig. 2. (a) The experiment setup for DFG. (b) Preliminary calculation result of optical isolation based on DFG.

As a conclusion, our work shows that nonmagnetic optical ioslator with complete isolation, high linearity, wide bandwidth can be achieved by using nonlinear frequency conversion or through four wave mixing.

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